NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3990

EFFECT OF CRYSTAL ORIENTATION ON FATIGUE-CRACK INITIATION IN POLYCRYSTALLINE ALUMINUM ALLOYS

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SUMMARY

It was determined that fatigue cracks initiate in preexisting slip-bands on planes that are parallel to (111) planes from tests on large-grained specimens of 1100 and 5052 aluminum alloys. The resolved shear stress on these planes in crystals where fatigue cracks had developed was compared with that in uncracked crystals. In bending fatigue tests the cracks always started in crystals at the corner of the cross section; this made comparison difficult, but it appeared that grain size and shape as well as resolved shear stress had an influence on the initiation of cracks. Under torsional loading the resolved shear stress appeared to be the only important factor that governed which crystal developed cracks.

INTRODUCTION

The work of Gough and Forrest (refs. 1 and 2) provides important information on the relation between the orientation of fatigue cracks and the crystallographic axes both in single crystals and in specimens containing a few crystals. They established that fatigue cracks initiated along preexisting slip systems in face-centered cubic crystals, that is on a (111) plane. Their work also indicated that in single crystals or in specimens containing two or three crystals fatigue failure was controlled by the shear stress resolved on the slip plane, and the normal stress had a negligible influence. Their work did not extend to a study of the factors influencing fatigue in polycrystalline metals where fatigue failure is influenced by such factors as grain size and shape and the restraining effect of adjacent grains.

The work reported herein was an attempt to obtain such information by comparing the magnitude of the resolved shear stress in cracked grains of a polycrystalline specimen with that in neighboring grains that did not contain cracks. The investigation was conducted with both torsion and bending fatigue loading.

This investigation was conducted at the National Bureau of Standards under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. The writers are indebted to Mr. Nathan Koenig for determining the crystal orientations and to Mr. H. C. Vacher for his assistance in interpreting the data.

SYMBOLS

F_L	location factor, σ/σ_{max} or τ/τ_{max}
F_O	orientation factor, highest shear stress on (111)-[110] system divided by nominal stress
F_R	resolved-shear-stress factor, $F_L F_O$
N	number of cycles to first observed crack
σ	calculated axial stress at particular point
σ_1,σ_3	maximum and minimum principal stresses
σ_{max}	calculated maximum axial stress in specimen
λ_1	angle between σ_1 and [110] direction
λ_2	angle between σ_3 and [110] direction
τ	calculated shear stress at a particular point
τ_{max}	calculated maximum shear stress in specimen
ϕ_1	angle between σ_1 and normal to (111) plane
ϕ_2	angle between σ_3 and normal to (111) plane

MATERIALS AND TEST PROCEDURE

Specimens were made from two aluminum alloys, 1100 (99+ percent aluminum) and 5052 (2.5 percent magnesium; 0.25 percent chromium). These alloys were selected because they are substantially free from precipitation or other phase changes and the desired grain size could be reproduced quite consistently by the strain-anneal method.

The specimen blanks were cut from commercial-quality 1/8-inch sheet, with the longitudinal axis of the coupon in the rolling direction of the sheet. The specimen blanks were treated in the following manner to obtain the desired grain size. The 1100 aluminum alloy was given a preliminary anneal at 1,020° F for 5 hours and furnace-cooled to room temperature. The material was then strained 2 percent in tension, reannealed at 925° F for 4 hours, and furnace-cooled to room temperature. The 5052 aluminum alloy was given a preliminary anneal at 925° F for 4 hours and furnace-cooled to room temperature. The alloy was then strained 10 percent, reannealed at 925° F for 4 hours, and cooled to room temperature.

The dimensions of the specimens machined from the large-grained strip are shown in figure 1, and typical grain sizes of the material can be seen in figure 2. Specimens of the above type were used for both bending and torsion tests. The finished specimens were given a macroetch, and those that did not have a satisfactory grain size were discarded. The remaining specimens were given a metallographic polish on one face and were finally lightly etched with a modified Keller's solution.

All bending fatigue tests were conducted on small Krouse sheet-bending machines operating at 1,750 revolutions per minute. The torsion tests were conducted on a Sonntag universal fatigue testing machine using a small torsion fixture that was especially designed for the specimens used in this investigation (fig. 3). In both types of tests the machines were stopped periodically during the test and the surfaces of the specimens were examined microscopically. In the torsion tests this was accomplished by means of a microscope located directly over the specimen, but in the bending tests it was necessary to remove the specimen from the machine. In many cases series of photomicrographs were taken to provide a record of changes occurring on the surface of the specimen. As soon as a definite fatigue crack had developed, the test was discontinued.

Determinations of crystal orientations were made from X-ray-diffraction back-reflection patterns. The 1100 alloy deformed to such an extent during the fatigue tests that the diffraction patterns taken after testing were not suitable for determining orientation. Consequently, it was necessary to obtain diffraction patterns for a number of grains in the areas of greatest stress before starting the test. Fortunately, in the 5052 aluminum alloy, excessive deformation occurred only in a small part of the grain in which the fatigue crack developed, and the remaining part of the grain gave satisfactory X-ray-diffraction patterns.

RESULTS AND DISCUSSION

As this investigation was directed primarily toward the factors influencing crack initiation, it was necessary to determine as accurately as possible when a fatigue crack was present. The difficulty of this determination has been discussed by a number of investigators (refs. 3 to 5) and is well illustrated by the series of micrographs in figure 4 showing the surface changes that occurred in the bending fatigue of an 1100 aluminum-alloy specimen. There is no discernible point at which it can be said that the slipbands have developed into cracks. Although the 5052 specimens did not show much slip prior to cracking in the bending fatigue tests, there was more evidence of slip in the torsion tests, and crack determination was again difficult. In order to provide information on this problem, sections of several specimens of both alloys were examined metallographically. Figures 5 and 6 both show the surface of large-grained specimens of aluminum alloys that were stressed in reversed torsion. Stressing of the specimen in figure 5 was stopped after appreciable marking of the surface had occurred, whereas the softer specimen in figure 6 was fractured in the fatigue test. Longitudinal sections through the areas shown in figures 5 and 6 were prepared for metallographic examination using a transparent mounting material so that the location of the section relative to the surface markings could be observed. There was at least one crack associated with each group of vertical markings in figure 5, typical examples being shown in figure 7. On the other hand, there were no cracks observable in the area indicated by bracket A in figure 6, although there were, of course, numerous cracks at other locations.

From a study of these and other specimens it was concluded that a crack having a depth of 0.0005 inch would be clearly discernible on sections prepared and examined in this way, and it seems probable that the marks in area A, figure 6, are slipbands and not cracks. If this is the case, one is led to the conclusion that it may be necessary to section and examine each specimen in order to distinguish between slipbands and cracks. This was obviously impractical, but several such examinations were made in order to assist the operator in judging when a crack was present on the basis of surface appearance. This made it possible to identify the crystal that first developed cracks before they had become large enough to have an important effect on the stress distribution in the specimen.

Figure 8 shows the number of stress cycles to the first observed crack N for bending and torsion[1] tests on the 5052 specimens. The graph is plotted in terms of the maximum shear-stress amplitude (one-half the axial stress for the bending case) and indicates that the fatigue strength

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[1]Stress calculations for the torsion specimen were based on formulas in reference 6.

under torsion loading is approximately twice that in bending. However, the data are not strictly comparable, as the bending tests were made on machines of the constant-deflection-amplitude type while the torsion tests were made under conditions of constant load amplitude. Also, the maximum stress in the torsion specimens occurred in the middle of the face, so the cracks initiated in a flat surface, whereas the cracks in the bending specimens formed at the corners of the reduced section. Finally, nominal stress values were used in both cases, and the effective stress concentration may have been higher in the bend specimens. The curves are presented therefore only as indications of the fatigue properties of the material.

The cracks in the bending specimens always started at the corners of the reduced section, as illustrated in figure 2, so that the orientation of the plane of the initial crack could be determined from its traces in the face and edge of the specimen. Then, using the orientation of the crystal obtained from the X-ray diffraction patterns, the (111)-[110] system[2] having the maximum resolved shear stress was computed. The normal to the (111) plane in each case was found to coincide with the normal to the initial crack plane within the anticipated precision of measurement. The (111)-[110] system having the highest resolved shear stress was also computed for a number of other grains near the minimum section, and the orientation factor was computed for both cracked and uncracked grains. (The orientation factor F_O is the highest shear stress on a (111)-[110] system divided by the nominal stress.)

In order to determine the relative magnitude of the stress applied to each crystal being studied, a curve (fig. 9) was prepared giving the stress variation near the reduced section. From this curve, each crystal was assigned a location factor $F_L = \left(\frac{\sigma}{\sigma_{max}}\right)$ based on its distance from the narrowest point. As most of the crystals studied were near the edge, the stress was assumed to be constant along lines perpendicular to the axis of the specimen. The product of the location factor and the orientation factor gave the ratio of the resolved shear stress in each crystal to the maximum resolved shear stress that might be applied to any crystal in that specimen. This ratio will be referred to as the resolved-shear-stress factor, $F_R = F_L F_O$.

The data from two specimens of 1100 alloy and three of 5052 are listed in table 1. In all of the 5052 specimens the cracked crystals had a higher resolved-shear-stress factor than neighboring uncracked crystals, but this was not true in the 1100 alloy specimens. In specimen 6 certain crystals with higher resolved-shear-stress factors than

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[2]Slip in aluminum occurs on (111) planes in the [110] directions. For convenience this will be referred to as the (111)-[110] system.

those of the cracked grains did not intersect the edge; it is well known (ref. 7) that the resistance to fatigue is less at a square corner than on a flat surface. This makes it difficult to compare the cracked crystal with any grains but other corner grains.

In 1100 alloy specimen 30 the cracked crystal (crystal 2, fig. 2) had a lower resolved-shear-stress factor than either of the crystals adjacent to it. The edge of this specimen is shown in figure 2(b). Grain 1 is thin and tapers to a point at the center of the reduced section, whereas grain 2 extends under 1 and occupies about half of the thickness of the specimen. This indicates that not only the resolved shear stress but also the free path for slip has an influence on the initiation of a fatigue crack with the crack tending to form in the crystal with the longest free path for slip. It is also significant that the crack formed in the interior of the grain and was not associated with any grain boundary.

Grain 3 in this specimen illustrates one of the difficulties encountered in trying to make comparisons of this type on bending test specimens. The clamped end of the specimen is at the right in figure 2; since the point of maximum stress is between the minimum section and the clamped end (fig. 9), this crystal had a high location factor even though it was some distance from the minimum section. The orientation factor was also high, but this may have been in error because the direction of the stress in the crystal was not parallel to the axis of the specimen. Particularly near the edge of the specimen where the crack would form, the stress direction would be expected to be nearly parallel to the edge, and this difference from the assumed direction might be enough to cause a significant error in the calculated orientation factor.

Because of the difficulties and uncertainties associated with the edges of the specimens in bending, more emphasis was placed on the torsion tests. The distribution of the stress across the minimum section, as shown in figure 10, is such that there is a considerable area of nearly uniform stress, and, of course, no stress at the corner of the section. Thus, the cracks started on a flat surface, eliminating the uncertainties mentioned above. This method of test introduced the difficulty that it was not possible to determine the plane of the crack, since its trace in only one plane was visible, but this was not considered too serious, since the results of the bending tests did not leave much doubt that the cracks started on the (111)-[110] system with the largest resolved shear stress.

Figure 11 shows the face of a torsion specimen at the conclusion of the test. The independent behavior of individual crystals is well shown by the small grain that has developed cracks or slipbands at right angles to those in the grain that surrounds it.

As it was not possible in these tests to determine the plane of the cracks, the assumption was made that the crack plane coincided with the (111) plane having a trace closest to the trace of the crack. This assumption was justified by the fact that there was good agreement between the two traces in all cases. The orientation factor was then determined as follows:

$$F_O = \frac{\sigma_1 \cos \phi_1 \cos \lambda_1 - \sigma_3 \cos \phi_2 \cos \lambda_2}{\sigma_1}$$

$$= \cos \phi_1 \cos \lambda_1 + \cos \phi_2 \cos \lambda_2$$

as the principal stresses in the surface are equal and opposite: $\sigma_1 = -\sigma_3$.

The location factor for the crystals involved two factors, one taken from figure 10 for the transverse variation of stress and the second, for the longitudinal variation which was assumed to be inversely proportional to the width of the specimen at the location of the crystal. The resolved-shear-stress factor, as in the bending case, was then given by $F_R = F_L F_O$.

The results of these calculations are listed in table 2 for five specimens of 5052 alloy. (No specimens of 1100 alloy were used in torsion because the excessive deformation made observation difficult.) The resolved-shear-stress factor of uncracked crystals was in no case larger than that of cracked ones, although there is one specimen (specimen 3) in which the factors for a cracked and uncracked crystal are equal. Thus, the data indicate that for this material and stress system the resolved shear stress is the only important factor influencing the initiation of torsional fatigue cracks. In order to give an idea of the general applicability of this conclusion, figure 12 shows the orientation of all crystals that were studied in the torsion tests on 5052 alloy specimens. It is apparent that a good sampling of orientations was obtained. In considering this figure it must be emphasized that the location of the specimen axis in the sterographic triangle does not provide sufficient information for determining the orientation factor for the crystal, as it is necessary to know the orientation relative to both principal stresses. Thus, it is not possible to draw "contour lines" of equal orientation factor for the torsion case although this can be done for uniaxial stress.

It will be noted from table 2 that there are more cracked grains in most of the torsion specimens than was the case in the bending tests. This is probably chiefly due to the greater area in which conditions are such that fatigue cracks can be initiated; however, the number of cracks per grain also appear to be larger than in bending, and this is apparently a result of the stress system. The number of cycles to form the first observed crack is listed in table 2; no particular significance is attached to this except insofar as the range of values indicates that the conclusions regarding the effects of orientation are not dependent on the stress level of the test.

CONCLUSIONS

The following conclusions are derived from the present investigation of the effect of crystal orientation on fatigue-crack initiation in aluminum alloys:

1. The observations of previous investigators were confirmed in that fatigue cracks were found to develop from preexisting slipbands and consequently the plane of the initial crack in the aluminum alloys tested was parallel to a (111) plane.

2. There was no evidence that grain boundaries or interaction with neighboring grains promoted the initiation of cracking.

3. The resolved shear stress on the (111) plane in the [110] direction appeared to be the only important factor that governed which crystals developed fatigue cracks under torsional loading.

4. Fatigue cracks always developed in crystals located at the corner of the cross section in the bending specimens even though crystals away from the corner sometimes had a higher resolved shear stress.

5. Rather limited data indicated that grain size and shape had a greater effect on the initiation of fatigue cracks in bending tests than in torsion; in bending tests the cracks tended to form in crystals offering the longest free path for slip.

6. It is not possible to distinguish definitely between slipbands and cracks without making a metallographic examination of a section through the specimen.

National Bureau of Standards,
Washington, D. C., May 28, 1956.

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TABLE 1.- BENDING TESTS

Alloy	Specimen	Crystal (a)	Location factor, F_L	Orientation factor, F_O	Resolved-shear-stress factor, F_R	Crystal at corner
1100	6	18	1.00	0.465	0.46	No
		19-C	1.00	.450	.45	Yes
		13-C	1.00	.439	.44	Yes
		17	1.00	.444	.44	No
		11	.70	.482	.37	No
		12	.80	.458	.37	No
	30	3	.97	.485	.47	Yes
		1	1.00	.451	.45	Yes
		2-C	1.00	.432	.43	Yes
5052	1	1-C	1.00	.490	.49	Yes
		4	.97	.468	.45	Yes
		3	.88	.476	.42	Yes
	3	1-C	1.00	.460	.46	Yes
		2	.80	.422	.34	Yes
	6	1-C	1.00	.478	.48	Yes
		3	.99	.412	.41	Yes
		2	.94	.389	.37	Yes

[a]Fatigue cracks were present in crystals having a C following the number.

TABLE 2.- 5052-ALUMINUM-ALLOY TORSION SPECIMENS

Specimen	Crystal (a)	Location factor, F_L	Orientation factor, F_O	Resolved-shear-stress factor, F_R	Cycles to first crack, N
4	8C	0.99	0.96	0.95	250×10^3
	6C	1.00	.92	.92	
	1C	.96	.94	.91	
	4C	.92	.98	.90	
	7C	.98	.86	.84	
	5	.87	.95	.83	
	2	.80	.93	.74	
	3	.96	.58	.56	
5	1C	.93	.96	.89	212
	4	.94	.91	.86	
	3	.98	.82	.80	
	5	.75	.90	.68	
	2	.74	.52	.39	
3	1C	.97	.83	.80	121
	5	.98	.82	.80	
	4	.93	.82	.76	
	2	.80	.91	.73	
	6	.98	.67	.66	
	3	.97	.66	.64	
15	1C	.93	.98	.91	100
	2C	.91	1.00	.91	
	4C	.90	.90	.81	
	3	.98	.57	.56	
10	1C	1.00	.95	.95	15
	5C	.99	.89	.88	
	7C	.93	.87	.81	
	6C	.98	.82	.80	
	2C	.80	.84	.67	
	3	.80	.81	.65	
	4	.93	.58	.54	

[a]Fatigue cracks were present in crystals having a C following the number.

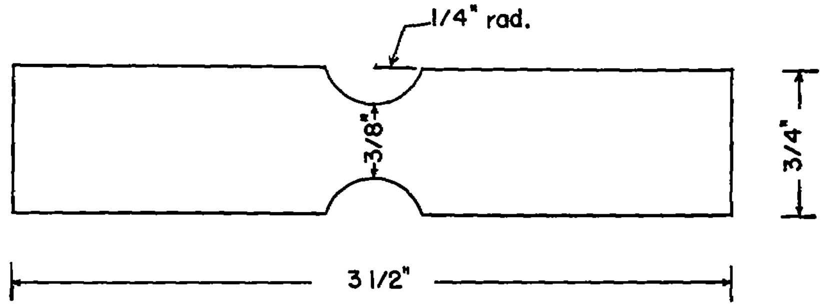
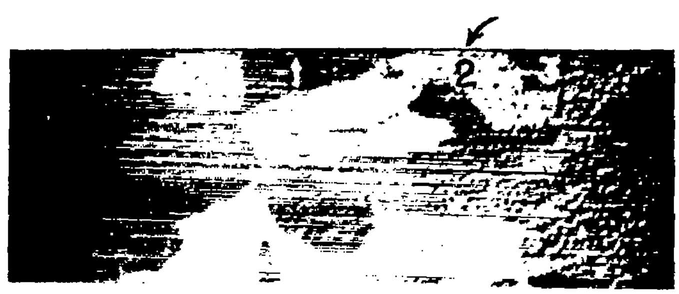


Figure 1.- Dimensions of specimens used for both bending and torsion tests.

(a) Face. Magnification, X5.



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(b) Edge. Magnification, X10.

Figure 2.- Typical large-grained specimen after testing in reversed bending. Arrows indicate fatigue crack in grain 2. Etched by aqua regia and hydroflouric acid.

Figure 3.- Torsion fixture for fatigue testing machine. S, specimen; P, moving platen.

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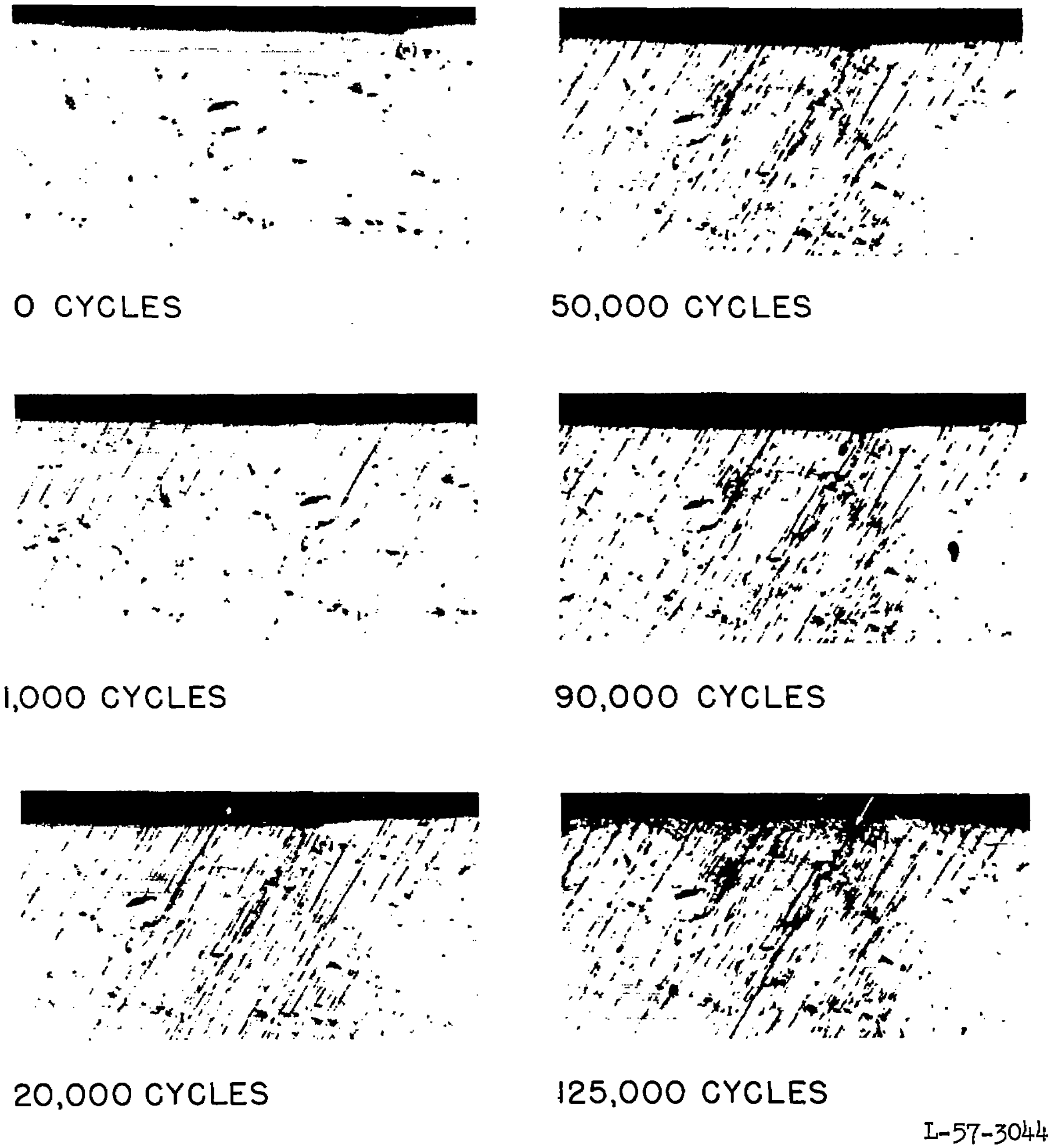

Figure 4.- Development of a fatigue crack (arrow) in an 1100 alloy specimen stressed in bending. Figures illustrate difficulty of determining when a crack forms; Keller's etch; magnification, X75.

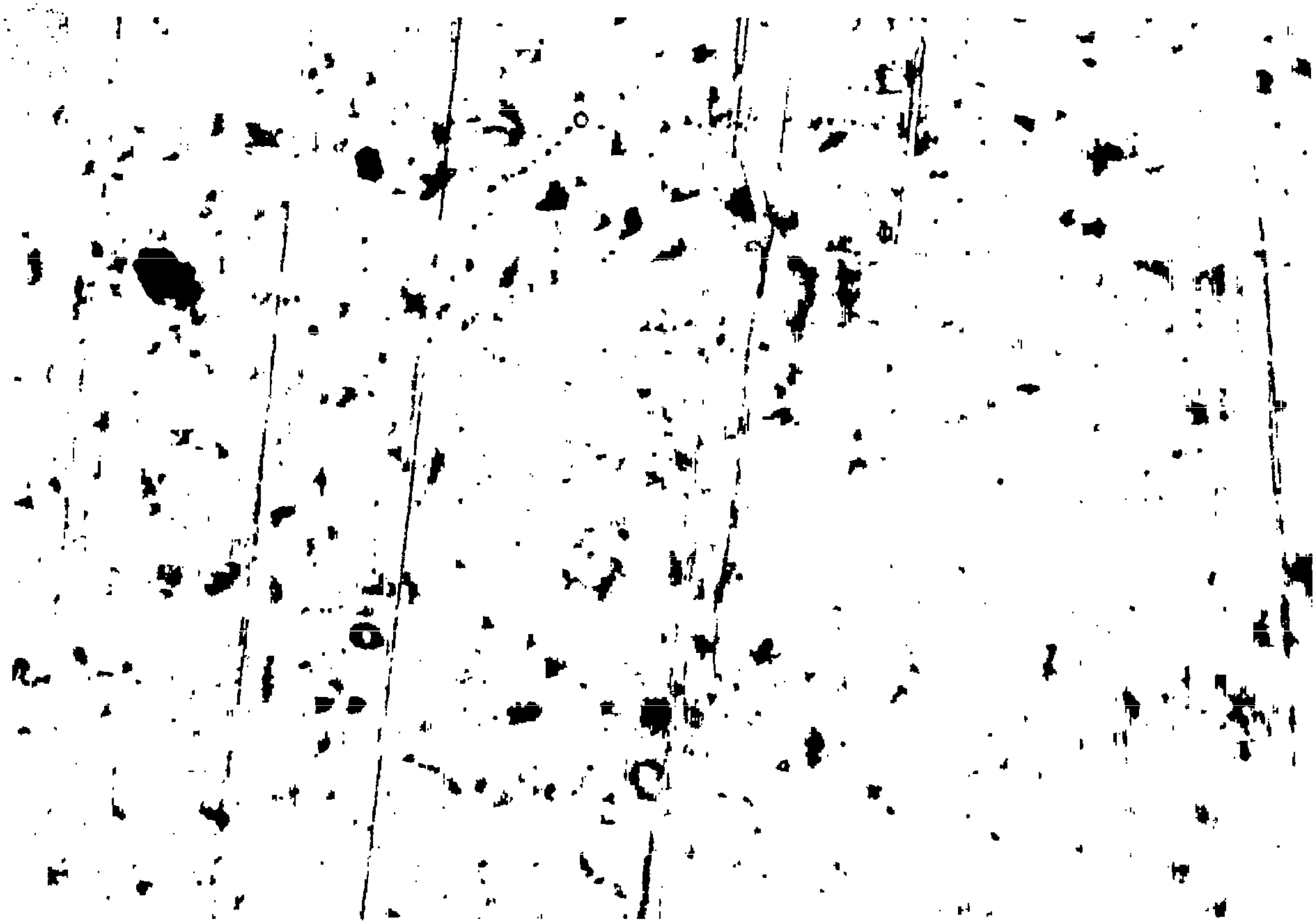

Figure 5.- Surface of 5052 alloy specimen stressed in reversed torsion. Axis of specimen horizontal; Keller's etch; magnification, X200.

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Figure 6.- Surface of 1100 alloy specimen fractured in reversed torsion. Axis of specimen horizontal. Dark band indicates trace of surface that was prepared for metallographic examination. Although numerous cracks were present, none were found in area indicated by bracket A. Keller's etch; magnification, X150.

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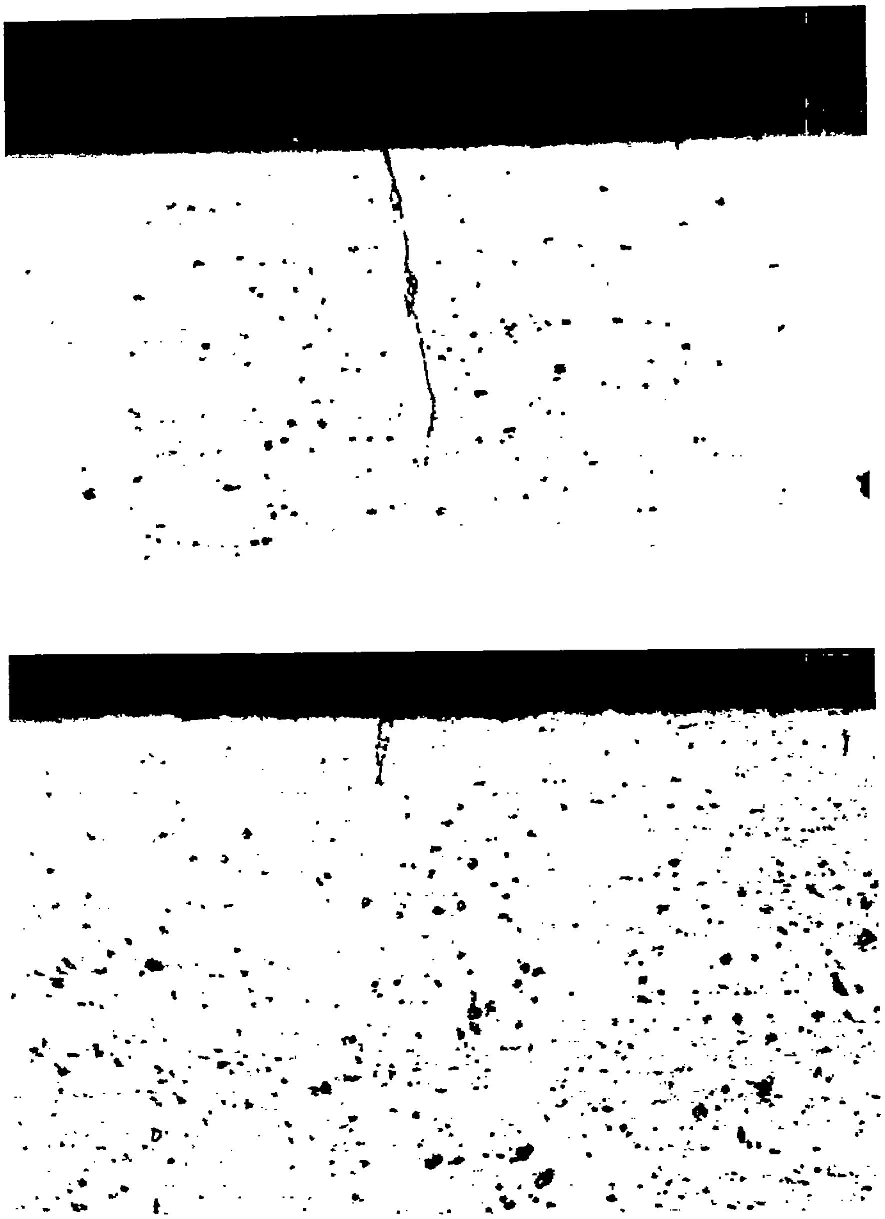

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Figure 7.- Typical cracks on a longitudinal section of specimen shown in figure 5, lightly etched in Keller's etch. Magnification, X250.

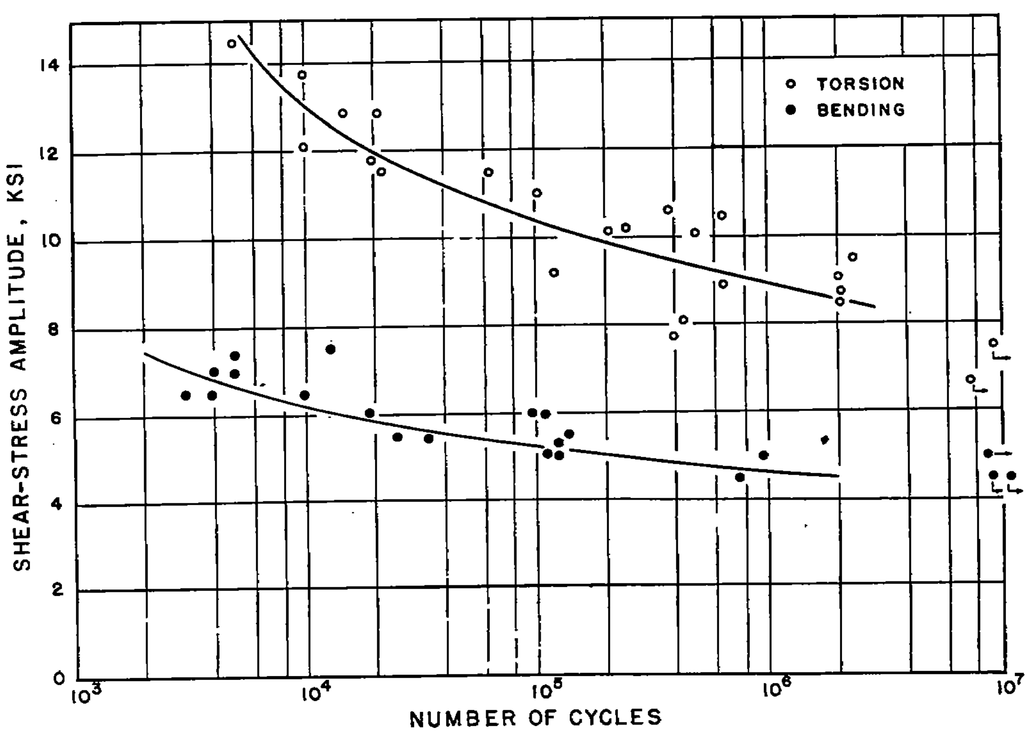

Figure 8.- Relation of shear-stress amplitude to number of cycles to initiate cracking in 5052 alloy specimens.

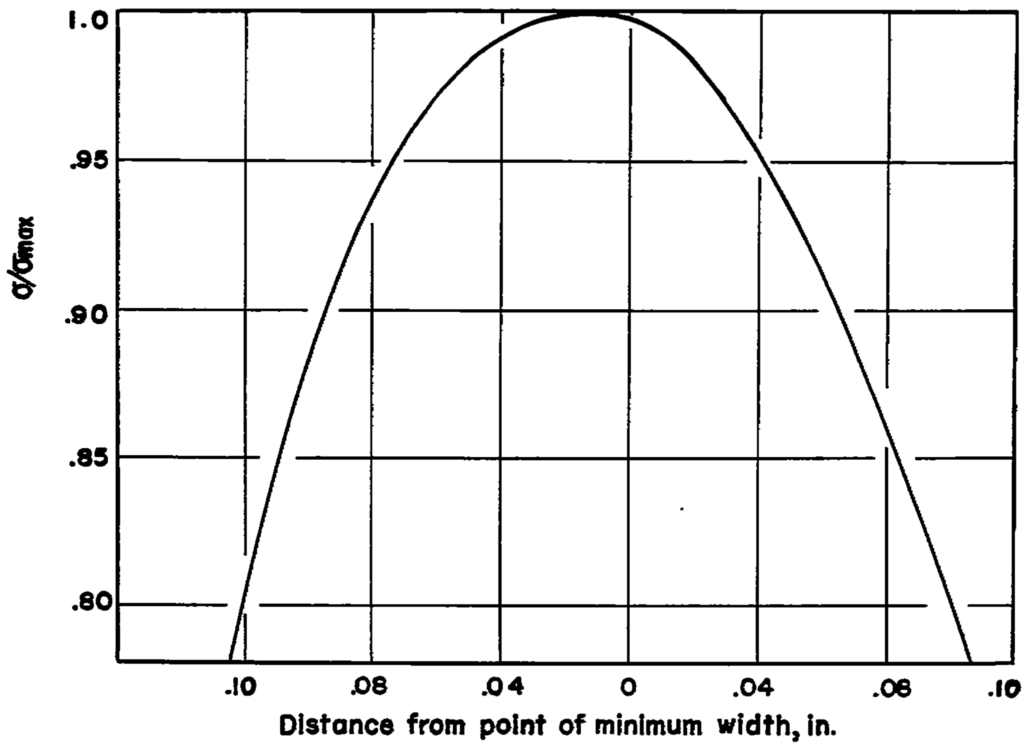

Figure 9.- Variation of stress ratio in reduced section of a specimen loaded as a cantilever. Abscissa scale indicates distance from point of minimum width, fixed end of specimen being at left.

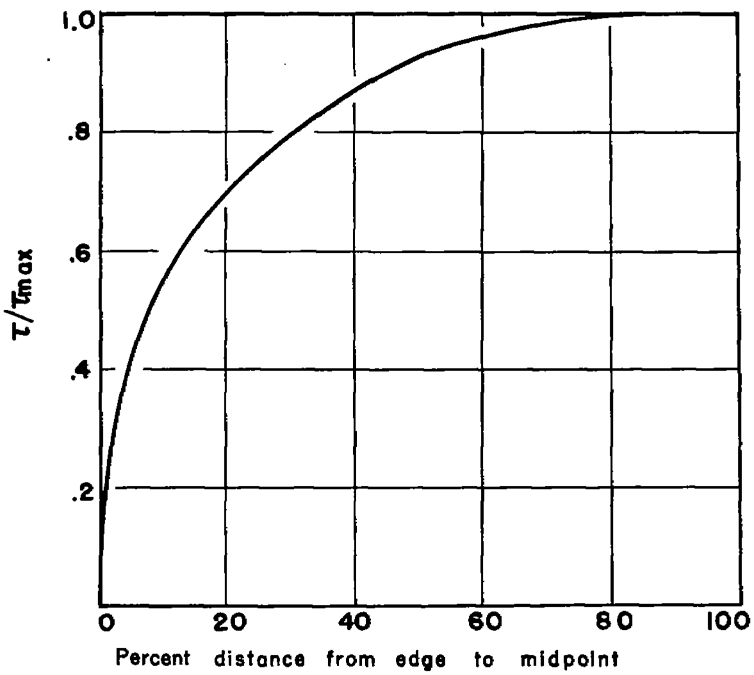

Figure 10.- Variation of shear stress ratio across a specimen loaded in torsion.

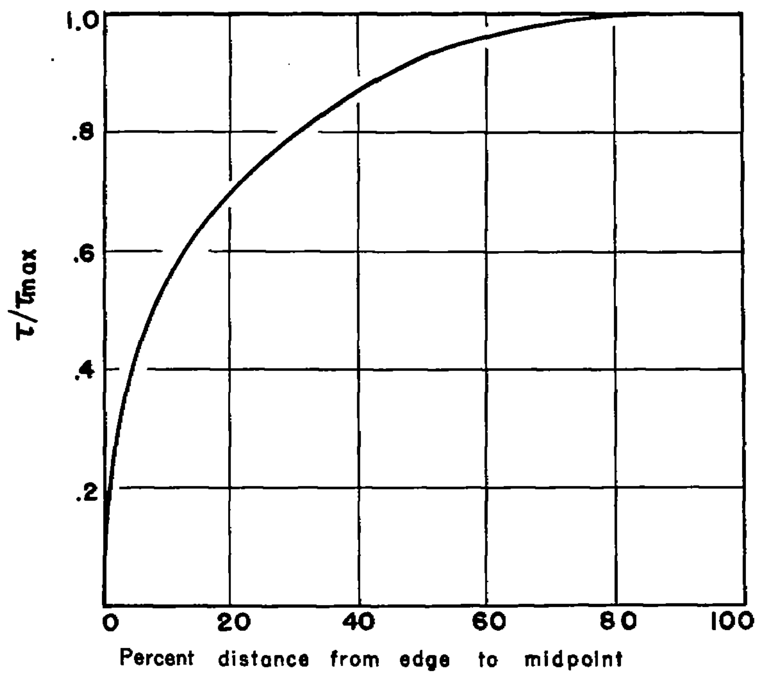

Figure 10.- Variation of shear stress ratio across a specimen loaded in torsion.

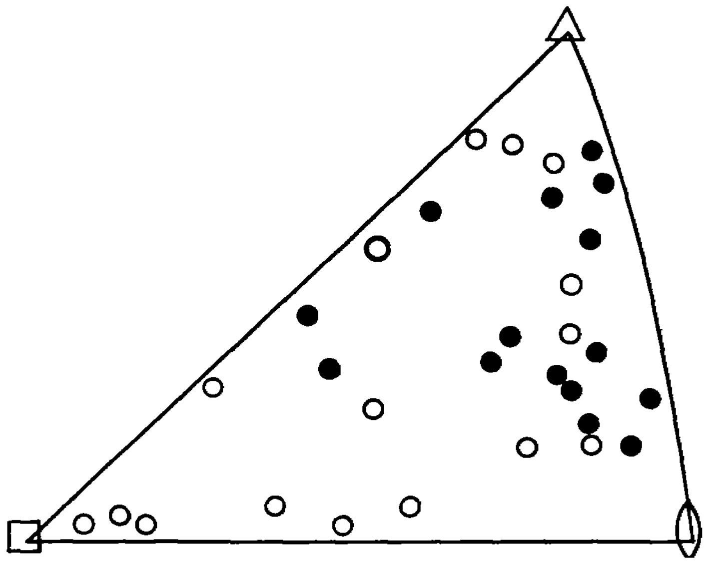

Figure 12.- Orientation of specimen axis relative to crystal axes of each grain listed in table 2. Closed circles, cracked grains; open circles, uncracked grains.